





Harmony Search Algorithm for Solving Combinatorial Optimization Problems: Bibliometric Analysis

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ABSTRACT

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The Harmony Search Algorithm (HSA) is a nature-inspired algorithm that emulates the improvisational process of musicians and has been successfully applied to various optimization problems across diverse domains. While numerous studies have reviewed and surveyed the HSA, to the best of our knowledge, no bibliometric analysis of the algorithm's applications in the context of Combinatorial Optimization Problems (COPs) has been conducted within the Scopus database prior to this research. This study aims to provide a comprehensive bibliometric analysis of HSA applications in COPs by examining a total of 2134 articles. The descriptive and bibliometric analyses focused on identifying the most productive journals, leading researchers, highly cited articles, prolific countries in HSA research, and potential future directions. The results indicate that the *Advances in Intelligent Systems and Computing* journal has published 93 articles, accounting for 4.358% of the total publications. Geem emerged as a prominent figure in the field, with 88 documents and 11,489 citations since 2001, as determined using the RStudio software. In terms of country-wise contributions, China ranked first, producing 592 HSA-related documents. This analysis offers valuable insights for researchers and practitioners engaged in HSA applications within the realm of COPs.

1. INTRODUCTION

Real-world problems can be broadly categorized into two classes: optimization problems, such as transportation and supply chain optimization, and decision problems, such as the Traveling Salesman Problem (TSP). Decision problems generally require selecting a yes or no response, whereas optimization problems entail finding the optimal (minimum or maximum) value given a cost function. Optimization problems can be further divided into two subcategories: discrete problems with discrete variables and continuous problems with continuous variables [1]. In this context, the area of discrete optimization problems is referred to as Combinatorial Optimization Problems (COPs). The field of COPs encompasses a wide range of applications, including scheduling applications (e.g., job-shop and nurse scheduling) and transportation applications (e.g., traveling salesman and vehicle routing), among others. Moreover, problems within the COPs domain are typically considered NP-hard.

Optimal solutions for all NP-hard problems in the COPs field can be obtained using exact algorithms such as branch and bound; however, large instances of these problems often remain exceedingly difficult to solve optimally within an acceptable time frame. Consequently, approximate algorithms have been developed to address NP-hard problems. Meta-heuristic algorithms, like the genetic algorithm (GA), are

among the most notable of these algorithms. Furthermore, this class of algorithms is capable of finding near-optimal solutions for large problem instances within a reasonable amount of time.

The Harmony Search Algorithm (HSA), a well-known metaheuristic algorithm, was introduced by Geem et al. [2] in 2001. Inspired by the musical improvisation process, HSA emulates how musicians search for the perfect notes to create harmony. Based on this concept, HSA was designed to find suitable solutions to optimization problems [3]. The algorithm has demonstrated considerable success in various applications, encompassing fields such as computer science, engineering, and medicine. According to Ala'a et al. [4], the advantages of HSA include its simplicity, ease of programming, compatibility with other meta-heuristic algorithms, rapid determination of high-performance zones in the solution space, and adaptability to discrete or continuous optimization problems as well as decimal and binary alphabets. These features have garnered the attention of researchers and practitioners, leading to the exploration of HSA's applications in various domains, including COPs. Although numerous recent studies have reviewed and surveyed HSA [3, 5, 6], to the best of our knowledge, no bibliometric analysis of HSA has been conducted within the Scopus database prior to this research. Furthermore, bibliometric analysis has recently attracted significant interest from researchers, as it not only provides an overview of a field's progress but also paves the

way for future research. Additionally, young researchers can use bibliometric analysis to identify a starting point for their own investigations, rather than becoming overwhelmed by the multitude of articles [7]. Consequently, this study aims to present a bibliometric analysis of HSA by addressing the following questions:

- Q1: Which journals have the highest number of HSA publications?
- Q2: Who are the leading researchers in the field, and what are the most cited articles and most productive countries in HSA research?
- Q3: What is HSA's contribution to the field of Combinatorial Optimization Problems (COPs)?
- Q4: What are the future directions of HSA research?

The remainder of this paper is structured as follows: Section 2 presents an overview of the Harmony Search Algorithm (HSA); Section 3 comprises the bibliometric analysis; and Section 4 discusses the conclusions.

2. HARMONY SEARCH ALGORITHM (HSA)

A recently developed method is called the Harmony Search Algorithm (HSA) which draws inspiration from nature and imitates the improvisational style of musicians [5]. Numerous optimization problems in different domains have seen success with the technique. We discover that the technique has been employed in numerous fields, as indicated in Figure 1, based on the documents that were used as data for this study and were obtained from the Scopus database.

Numerous research has provided detailed descriptions of the algorithm's operation processes. Therefore, in this study,

we will limit ourselves to providing a flowchart of these procedures in Figure 2, which were just recently introduced in the literature by the study [5], in order to prevent repetition.

HSA has been actively researched and used to solve a variety of COPs since its debut in 2001. The research landscape on using HSA to solve COPs is not yet completely surveyed, nevertheless. A bibliometric analysis can give a quantitative and qualitative evaluation of the research output, pinpoint the most significant scholars, organizations, and journals, and highlight the recurring themes and patterns in this area of study. As a result, the purpose of this work is to perform a bibliometric analysis of the literature on the use of HSA in COPs. The findings of this analysis can help researchers navigate the body of existing literature on this subject while also shedding light on the condition of the field's research at the moment and prospective future research directions.

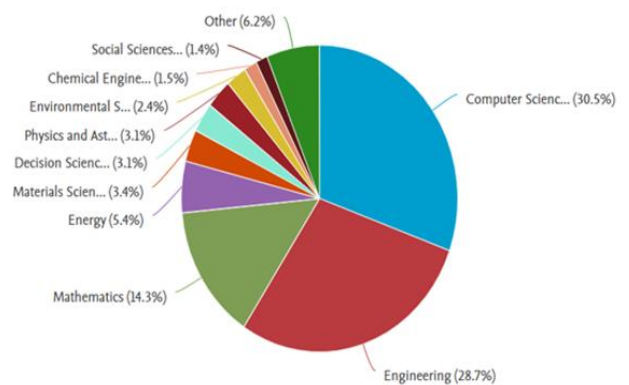


Figure 1. Documents by area in the Scopus database

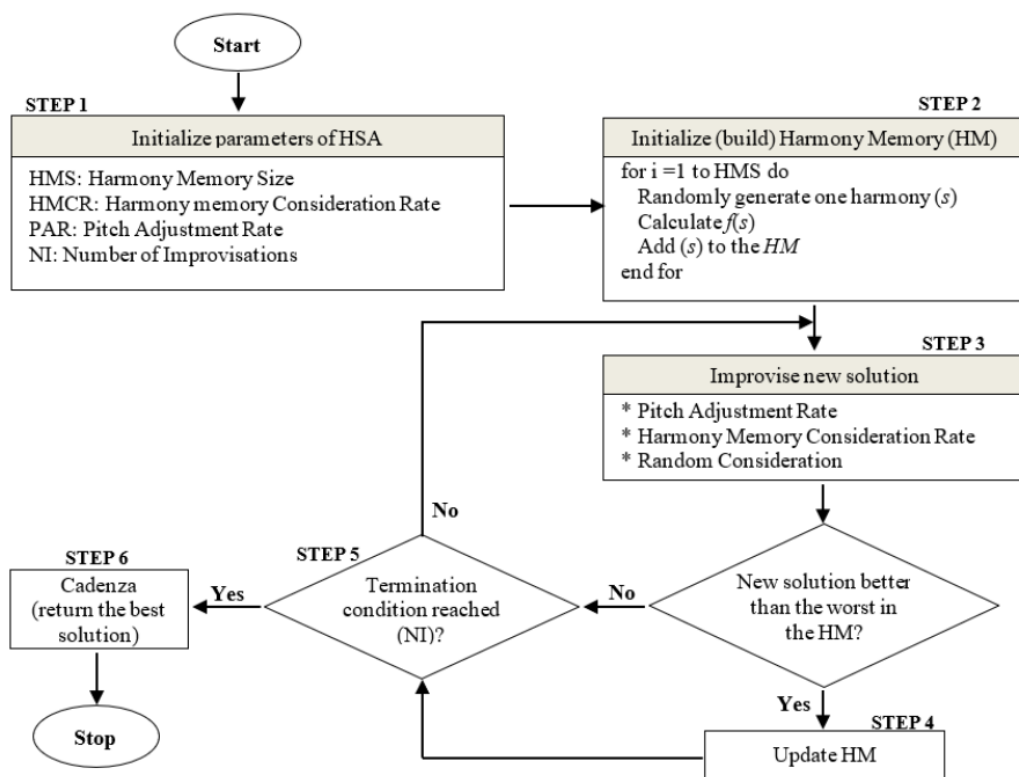


Figure 2. Flowchart of the basic HSA's components [5]

3. BIBLIOMETRIC ANALYSIS

A document system and the bibliometric properties of the individual documents are the research objects of bibliometric analyses. In this way, mathematical and statistical techniques are used to investigate the underlying science’s structure, characteristics, and patterns [8]. The Scopus database contained 2184 articles related to HSA based on specific terms like (“Harmony Search” OR “Harmony Search Algorithm”); (“Harmony Search Algorithm” AND “Combinatorial Optimization Problems”) a total of 2134 articles from HSA were used for this study’s descriptive analysis, bibliometric analysis that included determining the most productive journals of HSA documents, identifying top researchers in the area, most cited articles, most productive countries of the HSA, and future tracks of HSA. Between 2001 and 2022, the articles were released. The implementation of a thorough science-metric analysis was made possible by the fact that it has proven to be an effective method in bibliometric studies and reviews. To demonstrate the outcomes of the HSA evaluation in a manner that is simple to comprehend, we used Mendeley, Microsoft Excel, VOSviewer, and RStudio, an open-source software program. The following details regarding the articles included in this study are presented in Table 1 by using RStudio software:

Table 1. Information about articles

Description	Results
MAIN INFORMATION ABOUT DATA	
Timespan	2001:2022
Sources (Journals, Books, etc.)	949
Documents	2134
Annual Growth Rate %	19.34
Document Average Age	6.82
Average citations per doc	22.29
References	52355
DOCUMENT CONTENTS	
Keywords Plus (ID)	8542
Author’s Keywords (DE)	4168
AUTHORS	
Authors	3546
Authors of single-authored docs	86
AUTHORS COLLABORATION	
Single-authored docs	130
Co-Authors per Doc	3.24
International co-authorships %	18.49
DOCUMENT TYPES	
Article	1247
Conference Paper	795
Book Chapter	43
Review	18
Note	12
Conference Review	7
Erratum	6
Editorial	1
Short Survey	1
Retracted	1
Undefined	1

The HSA was proposed in 2001, and during that year, another study that also employed this algorithm was conducted. From 2002 to 2004, one study per year was conducted, according to the results of the descriptive analysis of the data used in this study. Production then went up from 2005, when

5 documents were created. The number of documents produced by using the HSA reached 15 in 2007, a notable rise. Following that, the number of documents produced increased during the years 2008, 2009, 2010, 2011, 2012, and 2013, reaching 25, 84, 131, 131, 132, 178, and 186, respectively. Figure 3 shows those results as follows.

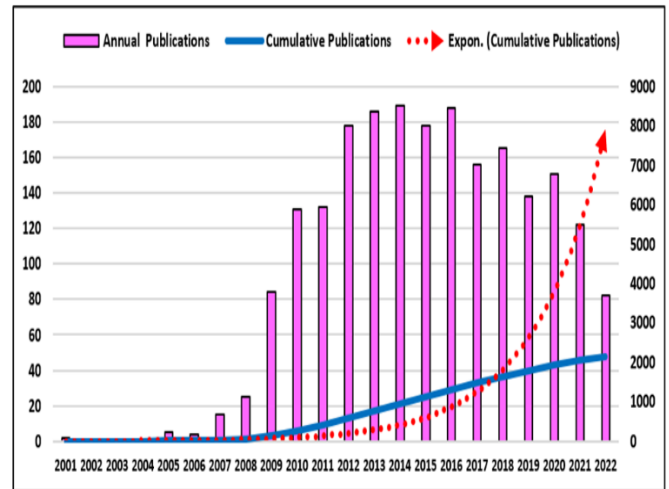


Figure 3. Articles published from 2001 till 2022

On the other hand, the increase in productivity, which reached 189 documents in 2014, demonstrates how widely used HSA has been by academics in a variety of subjects. The overall number of publications has expanded dramatically, with a total document production of 1180 from 2015 to 2022, due to the continual rise in the number of annual articles. It should be noted, though, that most of these articles require users to pay in order to access them. The following Figure shows articles published from 2001 till 2022.

3.1 Journal analysis

In addition to the number of citations, this component of the analysis lists the most significant publications that publish the most HSA documents by using VOSviewer software. By examining the data, we can see that the advances in intelligent systems and computing have published 93 articles, making it the most productive among all journals because it represented 4.358% of all articles published. With 63 publications or 2.952% of all published articles, applied mathematics and computation came in second place. Third place went to the applied sciences (Switzerland), with 40 publications and a proportion of 1.866 of all articles published. With regard to the number of citations, "Lecture Notes in Computer Science (including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)" occupied the top spot in terms of the number of citations, as it received the most citations, totaling 3,965 citations, and the number of documents reached 22 publications. The "International journal of electrical power and energy systems" came in second place after accumulating citations that totaled 2129 and publications that totaled 23. When the number of articles reached 32 papers from HSA, and the number of citations reached 1696, "Applied Soft Computing Journal" came in third. Table 2 includes the results of this analysis as follows.

Table 2. Top ten most productive journals of HSA

Source	Documents	Citations
Advances in intelligent systems and computing	93	289
Applied mathematics and computation	63	615
Applied sciences (Switzerland)	40	824
Applied soft computing journal	32	1696
Engineering optimization	31	1540
Expert systems with applications	28	267
International journal of electrical power and energy systems	23	2129
Lecture notes in computer science (including subseries lecture notes in artificial intelligence and lecture notes in bioinformatics)	22	3965
Soft computing	21	1102
Studies in computational intelligence	21	500

The VOSviewer program’s bibliographic coupling between the sources (journals) reveals that there are three clusters, the first of which is highlighted in red, the second in green, and the third in blue. The first cluster is represented by advances in intelligent systems and computing, with 74 links and a total link strength of 69014, then studies in computational

intelligence with 74 links and a total link strength of 33568 for the second cluster, and expert systems with applications with 74 links and a total link strength of 39911 for the third cluster. Figure 4 shows this coupling between the sources (journals) as follows.

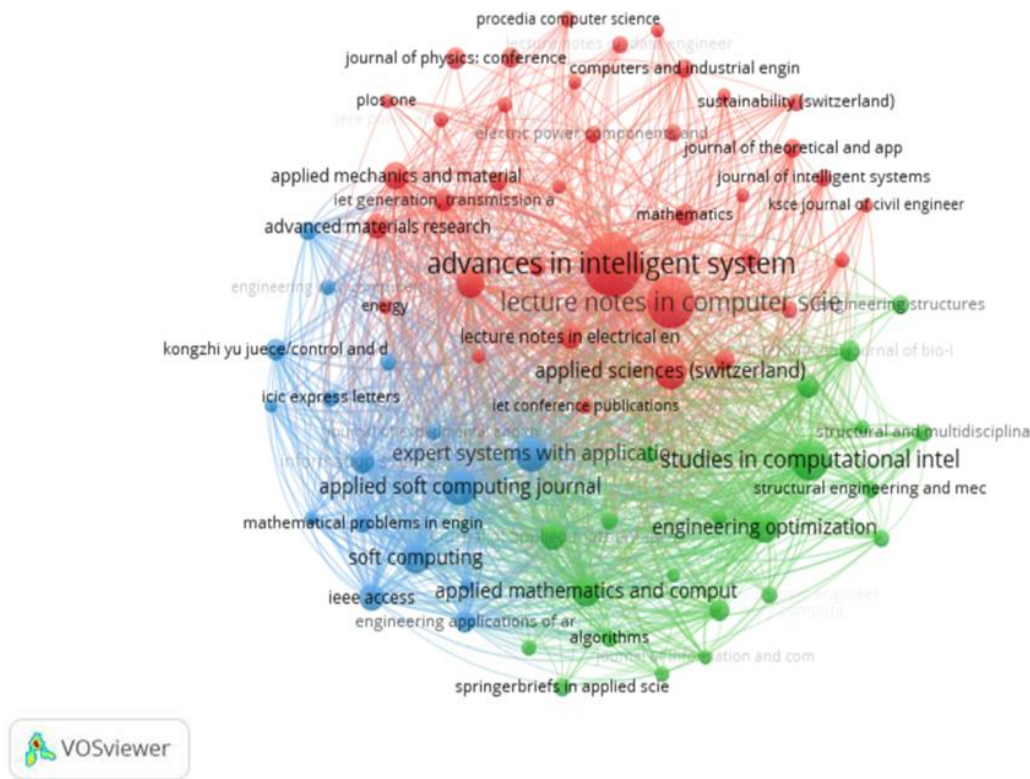


Figure 4. Bibliographic coupling among the Journals/ Sources

3.2 Top authors on HSA

Based on our data gathered from the Scopus database and utilizing RStudio software, this part contained an examination of the top writers who introduced HSA documents. The following measurements and acronyms were used in this analysis:

The total number of publications is NP; while the total number of citations is TC; the h-index is calculated as h has at least h papers that have been cited h times; the g-index is calculated based on the distribution of citations received by a given researcher’s publications; the m-index takes into account the years since first publication and is more relevant to an earlier career researcher than the h-index, and PY_start

is the starting year of publication.

The author GEEM ZW came out on top in this analysis using the RStudio software with a total of 88 documents and 11,489 citations since 2001, in addition to the statistical metrics h-index, g-index, and m-index, the author has scores of 33, 88, and 1.5 respectively. With a total of 35 documents and 1,214 citations since 2009, author GAO L then took second place and received 14, 34, and 1 from the h-index, g-index, and m-index, respectively. While KHADER AT, which has written 35 documents and received 1,002 citations altogether since 2008, finished third with scores of 19, 31, and 1.267 from the h-index, g-index, and m-index, respectively. The top ten authors of HSA who produce the most documents are listed in Table 3 as follows.

Table 3. Top ten most productive authors of HSA

Author	h_index	g_index	m_index	TC	NP	PY_start
GEEM ZW	33	88	1.5	11480	88	2001
GAO L	14	34	1	1214	35	2009
KHADER AT	19	31	1.267	1002	35	2008
AL-BETAR MA	18	30	1.2	954	33	2008
LI S	13	30	0.929	1104	30	2009
KIM JH	10	28	0.455	5445	28	2001
DEL SER J	12	26	0.923	951	26	2010
WANG L	14	25	1	944	25	2009
PAN Q-K	13	24	0.929	1151	24	2009
WANG X	13	23	0.867	613	42	2008

Figure 5 show the bibliographic coupling between authors by using VOSviewer, the yellow-colored cluster refers to the author GEEM ZW, who has 74 links with a 3154 total link strength. While the red-colored cluster refers to author GAO L

has 64 links with other authors, making up a total link strength of 885. The author KHADER AT in the blue cluster has 57 links and a total link strength of 634.

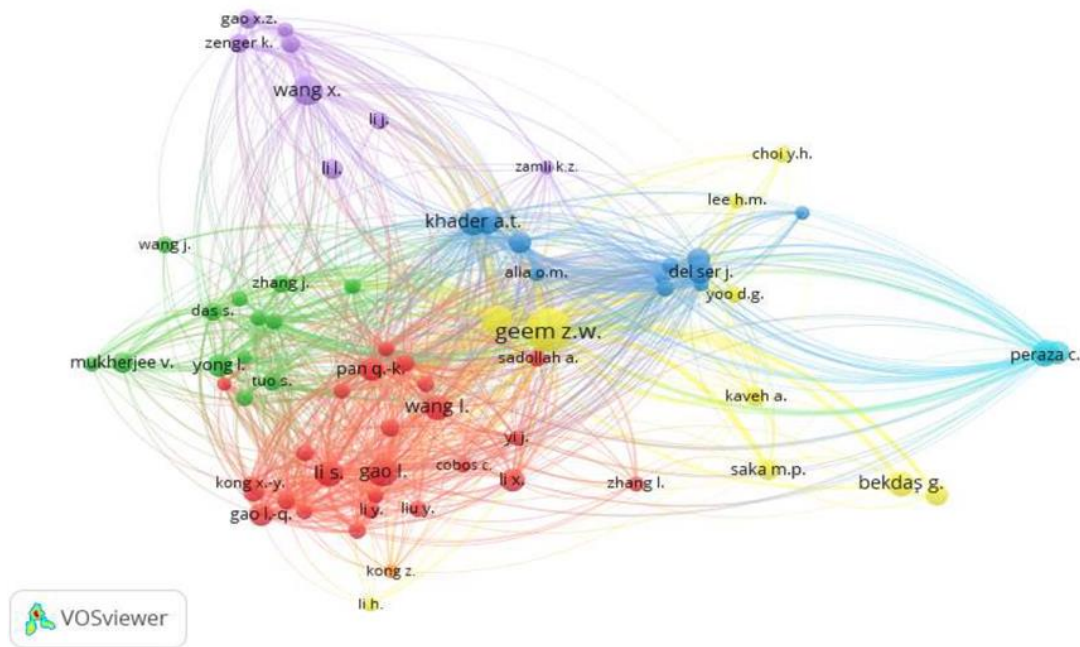


Figure 5. Bibliographic coupling between authors

3.3 Article citation analysis

An examination of the citations used by the writers to produce their works using RStudio software is included in this section. The following table lists the top ten HSA articles based on the total citations (TC) for each article in addition to including the title of an article (TI), source (SO), and digital object identifier (DOI). The analysis’s findings revealed that

GEEM et al. had written the majority of the first ten articles, and their articles took the top three spots. The article with the most citations, 4,577, was written by Geem and published in the source SIMULATION, released in 2001 under the title A NEW HEURISTIC OPTIMIZATION ALGORITHM: HARMONY SEARCH. This analysis is detailed as follows in Table 4.

Table 4. Top ten HSA articles based on the number of citations

Author	Year	TI	SO	DOI	TC
Geem et al. [2]	2001	A NEW HEURISTIC OPTIMIZATION ALGORITHM: HARMONY SEARCH	SIMULATION	10.1177/003754970107600201	4577
Lee et al. [9]	2005	A NEW META-HEURISTIC ALGORITHM FOR CONTINUOUS ENGINEERING OPTIMIZATION: HARMONY SEARCH THEORY AND PRACTICE	COMPUTER METHODS IN APPLIED MECHANICS AND ENGINEERING	10.1016/j.cma.2004.09.007	1504
Lee et al. [10]	2004	A NEW STRUCTURAL OPTIMIZATION METHOD BASED ON THE HARMONY SEARCH ALGORITHM	COMPUTERS AND STRUCTURES	10.1016/j.compstruc.2004.01.002	923
GEEM et al. [11]	2002	HARMONY SEARCH OPTIMIZATION: APPLICATION TO PIPE NETWORK DESIGN	INTERNATIONAL JOURNAL OF MODELLING AND	10.1080/02286203.2002.11442233	332

Kim et al. [12]	2001	PARAMETER ESTIMATION OF THE NONLINEAR MUSKINGUM MODEL USING HARMONY SEARCH	SIMULATION JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION	10.1111/j.1752-1688.2001.tb03627.x	312
Lee et al. [13]	2005	THE HARMONY SEARCH HEURISTIC ALGORITHM FOR DISCRETE STRUCTURAL OPTIMIZATION	ENGINEERING OPTIMIZATION	10.1080/03052150500211895	306
Manjarres et al. [14]	2013	A SURVEY ON APPLICATIONS OF THE HARMONY SEARCH ALGORITHM	ENGINEERING APPLICATIONS OF ARTIFICIAL INTELLIGENCE	10.1016/j.engappa.i.2013.05.008	292
Geem [15]	2008	NOVEL DERIVATIVE OF HARMONY SEARCH ALGORITHM FOR DISCRETE DESIGN VARIABLES	APPLIED MATHEMATICS AND COMPUTATION	10.1016/j.amc.2007.09.049	245
Geem [16]	2009	PARTICLE-SWARM HARMONY SEARCH FOR WATER NETWORK DESIGN	ENGINEERING OPTIMIZATION	10.1080/03052150802449227	204
Geem et al. [17]	2005	HARMONY SEARCH FOR GENERALIZED ORIENTEERING PROBLEM: BEST TOURING IN CHINA	LECTURE NOTES IN COMPUTER SCIENCE	10.1007/11539902_91	201

3.4 Most productive countries of HSA

With a percentage of about 49, China, India, and Iran are the first to produce the most documents on the HSA, with a total of 1239 documents out of 2521. Regarding citations, with a total of 12,379 citations, the United States came out on top. South Korea and Iran came in second and third, respectively, with 9,744 and 9,580 citations. The details of the outcomes of this analysis are summarized in Table 5.

There are 75 countries in total that are interested in the HSA. In the bibliographic coupling among the world's countries, we find 32 countries out of 75 countries that meet the threshold, assuming that each country has a minimum of 10 documents and 10 citations as a minimum. The results show there are 32 items distributed into 12 clusters, as shown in Figure 6.

Table 5. Top ten countries with the most document production of HSA

Country	Number of documents	Number of citations	Total link strength
China	592	7901	6283
India	366	5906	2823
Iran	281	9580	4570
Malaysia	161	2936	2259
South Korea	155	9744	4480
Turkey	123	4012	2016
United States	119	12379	5241
Australia	55	1754	1627
Spain	51	1305	689
Mexico	48	619	538

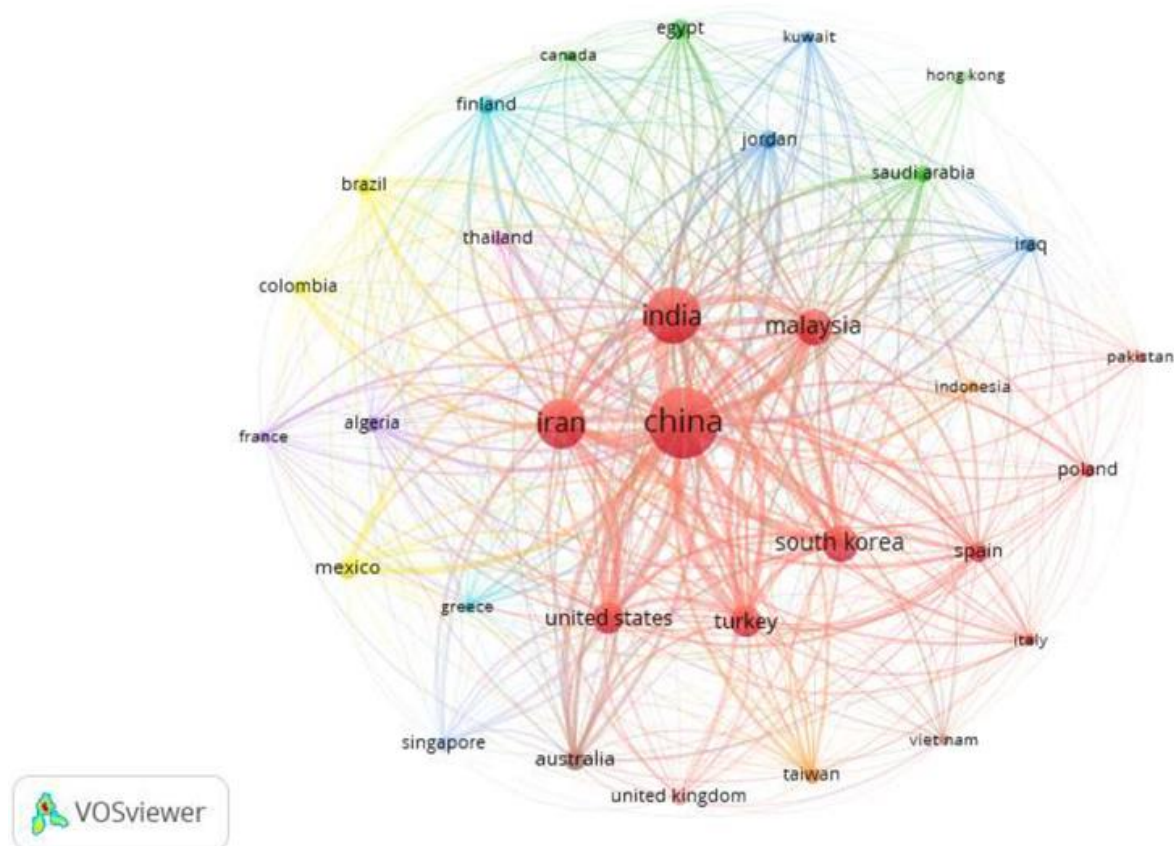


Figure 6. Bibliographic coupling among the countries

3.5 Applied HSA in the field of Combinatorial Optimization Problems (COPs)

As was already indicated, the topic of COPs has a large number of optimization issues that have been applied to numerous real-world domains. The HSA, like the other metaheuristic algorithms, was used extensively for the

majority of the problems in this area, the majority of which are compiled in the Table 6.

The most significant articles that employed the HSA to address different problems in the field of COPs are compiled in Table 7. On the other hand, the table includes author names and years, article titles, sources (journals), and citations.

Table 6. Combinatorial Optimization Problems that solved by using the Harmony Search Algorithm

Name of combinatorial optimization problem	Number of articles
Facility Location Problem	8
Location-Routing Problem	1
Flowshop Scheduling Problem	3
Job-Shop Scheduling	27
Knapsack Problems	26
Nurse Rostering Problem	13
Nurse Scheduling Problem	3
Traveling Salesman Problem	20
Vehicle Routing Problems	18
Capacitated Vehicle Routing Problem	2

Table 7. Most cited articles using the HSA in COPs

Author and Year	Title	Source	Cited by
Gholizadeh, R., Amiri, G.G., Mohebi, B. 2010	An alternative approach to a Harmony Search Algorithm for a construction site layout problem [18]	Canadian Journal of Civil Engineering	18
Gao, K.Z., Suganthan, P.N., Pan, Q.K., Cai, T.X., Chong, C.S. 2014	Pareto-based grouping discrete Harmony Search Algorithm for multi-objective flexible job shop scheduling [19]	Information Sciences	139
Wang, L., Pan, Q. K., Tasgetiren, M.F. 2011	A hybrid Harmony Search Algorithm for the blocking permutation flow shop scheduling problem [20]	Computers and Industrial Engineering	127
Zou, D., Gao, L., Li, S., Wu, J. 2011	Solving 0-1 knapsack problem by a novel global Harmony Search Algorithm [21]	Applied Soft Computing Journal	195
Hadwan, M., Ayob, M., Sabar, N.R., Qu, R. 2013	A Harmony Search Algorithm for nurse rostering problems [22]	Information Sciences	81
Awadallah, M.A., Khader, A.T., Al-Betar, M.A., Bolaji, A.L. 2011	Nurse scheduling using Harmony Search [23]	Proceedings – 2011 6th International Conference on Bio-Inspired Computing: Theories and Applications, BIC-TA 2011	18
Zou, D., Gao, L., Li, S., Wu, J., Wang, X. 2010	A novel global Harmony Search Algorithm for task assignment problem [24]	Journal of Systems and Software	68
Taha Yassen, E., Ayob, M., Ahmad Nazri, M.Z., Sabar, N.R. 2015	Meta-Harmony Search Algorithm for the vehicle routing problem with time windows [25]	Information Sciences	60
Pichpibul, T., Kawtummachai, R. 2013	Modified Harmony Search Algorithm for the capacitated vehicle routing problem [26]	Lecture Notes in Engineering and Computer Science	8
Misni, F., Lee, L.S. 2019	Harmony Search Algorithm for location-routing problem in supply chain network design [27]	ASM Science Journal	2

4. CONCLUSION

A technique for analyzing research literature known as "Bibliometric Analysis" entails quantitatively evaluating publishing trends, citation patterns, and other bibliographic data. The Harmony Search Algorithm (HSA) is used to solve Combinatorial Optimization Problems (COPs), and a bibliometric analysis of this algorithm is being done to evaluate its development and historical progression.

In this study, more than 2000 scientific papers that addressed the HSA and its real-world applications in numerous domains were reviewed and analyzed. Particularly, those issues fall under the purview of COPs. Together, descriptive analysis and bibliometric analysis provided the following answers to the questions posed by this research work.

Q1: Which journals have the most productions of the HSA?

The analysis in Section 3.1 provided an answer to this query, advances in intelligent systems and computing was the most productive journal overall with 93 papers published, accounting for 4.358% of all articles published overall.

Q2: Who are the top researchers in the area, and what are the most cited articles and most productive countries of the HSA?

The bibliometric analysis in Section 3.2 has provided an answer to this query in the form of the following findings:

With a total of 88 documents and 11,489 citations since 2001, as well as scores of 33, 88, and 1.5 for the statistical metrics h-index, g-index, and m-index, respectively, the author Geem emerged as the winner in this analysis using the RStudio software. A NEW HEURISTIC OPTIMIZATION

ALGORITHM: HARMONY SEARCH, written by Geem et al. and published in 2001 by source the SIMULATION, received 4,577 citations, making it the most-cited article. Furthermore, China, India, and Iran are the countries that produce the most HSA-related documents, with a percentage of approximately 49.

Q3: What is the contribution of HSA in the field of Combinatorial Optimization Problems (COPs)?

We discovered that the HSA has contributed to more than 120 publications addressing the majority of the most well-known problems in the field of COPs among the data gathered from the Scopus database for the purpose of conducting this research study. Please see Section 3.5 for a detailed explanation of the answer to this question.

Q4: What are the future tracks of HSA?

Despite all the benefits of the HSA, the topic of parameter tuning is still open because it depends totally on the features of the optimization problem that needs to be solved. As a result, there are no set values that work for all optimization situations. On the other hand, recent studies that focused on parameter tuning [5], did not discuss the use of optimization approaches to tune those parameters, such as the grid search technique [28]. Another trend for the future is to combine HSA with other metaheuristic algorithms to produce a more potent hybrid algorithm that can take advantage of the advantages of both algorithms to enhance solution quality and convergence speed. Although the HSA has been used to solve numerous optimization problems in COPs, to the best of our knowledge and the extent of this research work, we were unable to locate any studies in our data that focused on the hybrid approach between HSA with Ant Colony Optimization (ACO) to solve Quadratic Assignment Problem (QAP), which has a wide range of applications, including the health and educational sectors.

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